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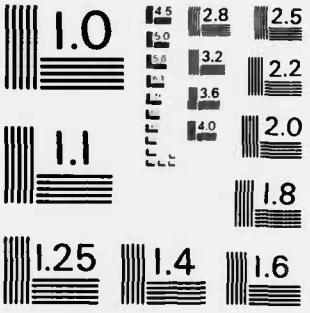

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Mechanical Properties of Longleaf Pine Treated with Waterborne Salt Preservatives

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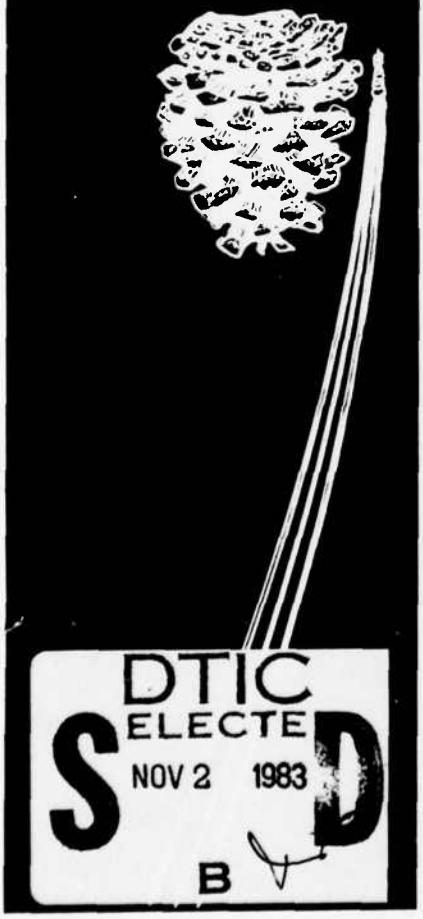

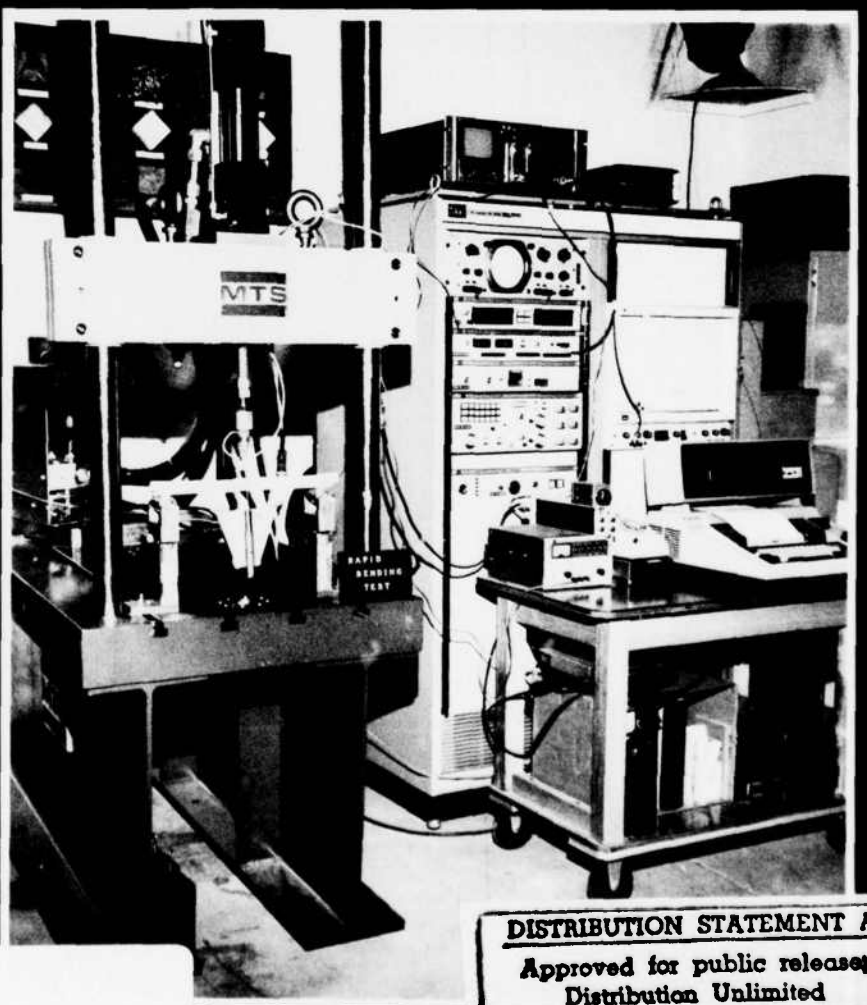

Abstract

lbs / cu ft

Mechanical properties were measured on small clear bending specimens of longleaf pine sapwood treated with three waterborne salt preservative systems. Preservative retentions ranged from 0.25 to 2.5 pounds per cubic foot (lb/ft³), and specimens were either air dried or kiln dried at 140°F. Modulus of elasticity of specimens dried at this schedule was not affected by preservative salt retentions of up to 2.5 lb/ft³.

Modulus of rupture was not affected by ACA treatments regardless of type of drying; was reduced by CCA-II at 2.5 lb/ft³ when kiln dried; and was reduced by CCA-I at retentions above 0.25, especially when kiln dried.

Work to maximum load was adversely affected by CCA-I and CCA-II at nearly all retentions when air dried or kiln dried and by ACA at retentions of 1.0 and 2.5 lb/ft³.

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Introduction

Waterborne inorganic salt preservatives, primarily chromated copper arsenate (CCA) and ammoniacal copper arsenate (ACA), are commonly used to protect wood in environments that promote decay. There is concern that these treatments may reduce the mechanical properties of wood, but the results of past research in this area (appendix I: **Literature**) are inconsistent and inconclusive, particularly at high loadings of salt. Better information is needed on the effects of these treatments so that compensation can be made in structural design using treated materials.

Small clear bending specimens of longleaf pine are used here to evaluate strength in response to treatment with ACA and CCA types I and II. A range of preservative retentions were tested from 0.25 to 2.5 pounds per cubic foot (lb/ft³). These retentions cover all normal use applications from above ground (0.25 lb/ft³) to marine environments (2.5 lb/ft³). Specimens were loaded very rapidly to simulate the load conditions of treated fender piles that failed during handling *(11)*.[3]

CCA Types I and II were selected for evaluation because they have substantially different proportions of chromium; ACA has no chromium. We believe that this heavy metal is capable of degrading wood properties.

[1] The Forest Products Laboratory is maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Verrill is a Mathematical Statistician, formerly of FPL, now at the Lawrence Livermore National Lab., Livermore, Calif. We acknowledge the computer assistance rendered by Eric Elvira of the Lawrence Livermore National Lab.

[3] Italicized numbers in parentheses refer to literature cited at end of report.

Methods

The experiment was a three-way factorial design:
- Preservative systems—three levels: ACA, CCA type I, and CCA type II.
- Salt loading—four levels: 0.25, 0.6, 1.0, and 2.5 lb/ft³.
- Drying—two levels: kiln and air drying.

There were also three "control" groups: water treated and kiln dried; water treated and air dried; and no treatment with air drying from the original green condition. A sample size of 25 specimens was provided for each preservative-retention-drying combination and the water-treated control groups. Thirty specimens were provided for the untreated control group.

- Specimens 1- by 1-inch-square and 16 inches long were prepared from longleaf pine logs and treated to target retentions by conventional practice. "Air-dry" specimens were dried under controlled conditions (initially 80°F and 90 pct relative humidity (RH) and finally 74°F and 65 pct RH). "Kiln-dry" specimens were dried for 10 days at 140°F, a condition intended to simulate drying of full-size piles. All specimens were allowed to come to equilibrium in an environment controlled at 74°F and 65 percent RH in preparation for test.

Specimens were tested in rapid bending by applying a concentrated load at the center of a 14-inch span. The duration of the test was about one-fiftieth of a second, and simultaneous measurements of load and deflection were recorded in a digital oscilloscope.

Appendix II contains experimental detail.

Results

Cell means, standard deviations, and numbers of specimens tested for modulus of rupture (MOR), modulus of elasticity (MOE), work to maximum load (WML), moisture content (MC), and specific gravity (SG) are given in tables 1–5.

Comparisons Between Preservative Systems, Retention Levels, and Type of Drying

A three-way analysis of variance (ANOVA) was performed to determine the significance of main and interaction effects of preservative systems, retention levels, and type of drying upon the three mechanical properties measured and upon MC. Data for the water-treated and the untreated control specimens were not included in this analysis.

At the 5 percent confidence level, the main effects of preservative systems, retention level, and type of drying were each significant on MOR, WML, and MC (table 6 and figs. 1–3). Figures 1 through 3 were constructed by combining the air-dried and kiln-dried results to best illustrate retention level and preservative system main effects. The effect of drying type was relatively minor except in the CCA-II case (fig. 4). There were no significant main effects on MOE.

There were no significant interactions of main effects on MOR. However, the preservative system-retention level interaction was significant on WML. From figure 2 it is apparent that the negative effect on WML of an increase in retention level is greatest in the CCA-I case, followed by the CCA-II case, and then the ACA case. This accounts for the interaction.

All interactions were significant on moisture content. In particular the increase of MC with an increase in retention level is more pronounced in the CCA-I case than in the CCA-II case (than in the ACA case) (fig. 3). This accounts for the preservative system-retention level interaction in the MC response.

Table 1.—Modulus of rupture (lb/in.²)[1]

Type drying	Untreated controls	Water-treated controls	Modulus of rupture of specimens treated at these retention levels (lb/ft³)[2]			
			0.25	0.6	1.0	2.5
				ACA		
Air dry	29 22,501 2,870(12.8)	25 22,164 2,657(12.0)	23 22,627 3,084(13.6)	25 21,716 3,311(15.2)	25 22,436 2,710(12.1)	25 20,716 2,591(12.5)
Kiln dry		25 21,135 3,748(17.7)	25 21,325 2,360(11.1)	24 21,952 2,910(13.3)	25 21,907 2,846(13.0)	24 20,854 3,346(16.0)
				CCA-I		
Air dry			24 21,332 2,676(12.5)	25 21,659 3,272(15.1)	24 20,492 3,081(16.0)	23 18,293 3,150(17.2)
Kiln dry			23 22,098 2,029(9.2)	25 20,219 3,301(16.3)	23 19,821 2,810(14.2)	24 18,944 3,445(18.2)
				CCA-II		
Air dry			25 22,515 3,079(13.7)	25 21,332 3,155(14.8)	23 22,255 2,740(12.3)	24 20,983 3,040(14.5)
Kiln dry			25 21,525 2,325(10.8)	22 20,435 2,291(11.2)	24 21,019 2,988(14.2)	24 20,011 3,271(16.3)

[1] In each set of data, the first line is the number of specimens; the second, the average modulus of rupture; the third, the standard deviation (coefficients of variation in parentheses).

[2] Nominal retention levels; actual retention levels are given in Table A1 in the Appendices.

Table 2.—Modulus of elasticity (10^6 lb/in.^{2})[1]

Type drying	Untreated controls	Water-treated controls	Modulus of elasticity of specimens treated at these retention levels (lb/ft^3)[2]			
			0.25	0.6	1.0	2.5
				ACA		
Air dry	29	25	23	25	25	25
	3.306	3.356	3.375	3.241	3.359	3.152
	0.551(16.7)	0.484(14.4)	0.490(14.5)	0.572(17.7)	0.424(12.6)	0.456(14.5)
Kiln dry		25	25	24	25	24
		3.126	3.217	3.344	3.377	3.238
		0.659(21.1)	0.387(12.0)	0.518(15.5)	0.546(16.2)	0.501(15.5)
				CCA-I		
Air dry			24	25	24	23
			3.179	3.292	3.183	3.352
			0.498(15.7)	0.535(16.2)	0.537(16.9)	0.429(12.8)
Kiln dry			23	25	23	24
			3.326	3.224	3.131	3.544
			0.322(9.69)	0.458(14.2)	0.476(15.2)	0.359(10.1)
				CCA-II		
Air dry			25	25	23	25
			3.301	3.238	3.367	3.200
			0.531(16.1)	0.483(14.9)	0.463(13.7)	0.519(16.2)
Kiln dry			25	22	24	24
			3.133	3.212	3.252	3.402
			0.486(15.5)	0.437(13.6)	0.482(14.8)	0.398(11.7)

[1] In each set of data, the first line is the number of specimens; the second, the average modulus of elasticity; the third, the standard deviation (coefficients of variation in parentheses).

[2] Nominal retention levels; actual retention levels are given in Table A1 of the Appendices.

A Duncan's multiple range test *(15)* was conducted to identify the source of significance in main effects. The results for comparisons among preservative systems are shown below.

(The symbols $<$ and $>$ indicate that a treatment leads to a strength property that is significantly less than or greater than another at the 5 pct confidence level; an equal sign indicates no significance at that confidence level.)

MOR: CCA-I $<$ CCA-II $=$ ACA
MOE: CCA-I $=$ CCA-II $=$ ACA
WML: CCA-I $<$ CCA-II $<$ ACA
MC: CCA-I $>$ CCA-II $>$ ACA

Similarly the results for level of salt retention are

MOR: 2.5 $<$ 1.0 $=$ 0.6 $=$ 0.25
MOE: 2.5 $=$ 1.0 $=$ 0.6 $=$ 0.25
WML: 2.5 $<$ 1.0 $=$ 0.6 $<$ 0.25
MC: 2.5 $>$ 1.0 $>$ 0.6 $>$ 0.25

and for type of drying

MOR: KD $<$ AD
MOE: KD $=$ AD
WML: KD $<$ AD
MC: KD $<$ AD

Because significance of interactions did not reflect degree of effect, we qualify these results. In particular, the nature of the significant preservative-retention level interaction in the WML case (fig. 2) suggests that the CCA-I $<$ CCA-II $<$ ACA ordering is much stronger at high retention levels than at low retention levels. In this same WML case the 2.5 $<$ 1.0 $=$ 0.6 $<$ 0.25 ordering is *more definite* for the CCA-I preservative than for the ACA preservative. Also in both the WML and MOR cases the KD $<$ AD result may be important *only* for the CCA-II preservative.

Figures 1 through 3 indicate that increases in MC generally parallel decreases in strength—i.e., for both MC and mechanical properties, ACA shows the least response to treatment, CCA-I the most, and these effects increase with increasing retention levels. To determine whether the lower mechanical properties were due to chemical degradation or to higher moisture contents, a second ANOVA was conducted on the MOR and WML data after adjusting individual observations to 12 percent MC *(20)*. Contrasting

the results of this analysis (table 7) to those in the unadjusted case (table 6), we see that the significant main effects of preservative system and retention level on MOR are apparently due to differences in MC. When the MOR data are adjusted to 12 percent MC, only the main effect of drying type is significant.

For WML, there is essentially no change in the levels of significance for all main and interaction effects when the data are adjusted to 12 percent MC. This analysis suggests that the salt treatments cause a degradation of the wood that affects WML but not MOR. Alternatively, it suggests that the standard WML moisture content adjustment is not satisfactory.

Regression

Although linear and nonlinear curves may be fit to the MOR or WML versus retention level data, the experiment was not specifically designed to provide optimal estimates of such curves. Thus we made no extensive curve-fitting efforts. We did, however, perform multiple regressions of MOR and WML on retention level and SG for the ACA-air dry, ACA-kiln dry, CCA-I, CCA-II-air dry, and CCA-II-kiln dry cases (data not adjusted for MC). No statistically significant lack of fit was detected. The resultant regression equations together with the corresponding confidence surface equations are given in table 8.

Properties of Treated Material Compared to Those of Untreated Controls

To determine the magnitude of treatment effects, the ratios of the average mechanical properties for each treatment group to those of the untreated control group were calculated (table 9). Also Duncan's multiple range test (DMRT) was used to test for significant differences (at the 5 pct level) between the averages of the treatment cells and the average of the untreated control group. This test was performed on both the unadjusted data and the data adjusted to 12 percent MC. The results of these analyses are included in table 9.

Table 3.—Work to maximum load (inch-pounds per specimen)[1]

Type drying	Untreated controls	Water-treated controls	Work to maximum load of specimens treated at these retention levels (lb/ft³)[2]			
			0.25	0.6	1.0	2.5
				ACA		
Air dry	29 250.9 49.3(19.7)	25 233.6 47.3(20.3)	23 233.7 52.7(22.5)	25 227.1 56.7(25.0)	25 232.8 45.0(19.3)	25 204.3 48.5(23.7)
Kiln dry		25 223.9 57.7(25.8)	25 221.9 48.3(21.8)	24 226.4 51.1(22.6)	25 211.9 39.6(18.7)	24 197.8 53.3(27.0)
				CCA-I		
Air dry			24 217.9 43.5(20.0)	25 209.0 50.2(24.0)	24 177.5 43.5(24.5)	23 118.9 42.4(35.7)
Kiln dry			23 226.6 40.4(17.8)	25 186.5 54.0(29.0)	23 168.7 35.8(21.2)	24 118.3 42.1(35.6)
				CCA-II		
Air dry			25 246.6 49.1(19.9)	25 212.5 54.4(256)	23 217.6 43.3(19.9)	25 186.8 43.5(23.3)
Kiln dry			25 246.9 41.9(17.0)	22 190.7 48.1(25.2)	24 191.1 47.8(25.0)	24 153.5 48.9(31.8)

[1] *In each set of data, the first line is the number of specimens; the second, the average energy absorbed to maximum load; the third, the standard deviation (coefficients of variation in parentheses).*

[2] *Nominal retention levels; actual retention levels are given in Table A1 of the Appendices.*

Table 4.—Average equilibrium moisture content of treated and untreated specimens[1]

Type drying	Untreated controls	Water-treated controls	Average equilibrium moisture content of specimens treated at these retention levels (lb/ft³)[2]			
			0.25	0.6	1.0	2.5
				ACA		
Air dry	13.3 (2.4)	13.6 (2.8)	13.9 (2.8)	13.8 (2.2)	14.1 (2.2)	14.4 (2.0)
Kiln dry		13.6 (2.4)	14.0 (3.1)	14.1 (2.7)	14.0 (5.0)	14.3 (3.2)
				CCA-I		
Air dry			14.1 (2.4)	14.3 (1.7)	14.7 (2.6)	16.7 (3.2)
Kiln dry			13.8 (2.7)	14.3 (2.1)	14.9 (2.3)	16.3 (3.2)
				CCA-II		
Air dry			13.8 (2.3)	14.0 (2.2)	14.4 (2.6)	15.7 (3.0)
Kiln dry			13.7 (2.3)	13.9 (2.6)	14.2 (1.9)	15.5 (2.6)

[1] Values in parentheses are coefficients of variation.

[2] Nominal retention levels; actual retention levels are given in Table A1 of the Appendices.

Table 5.—Average specific gravity of treated and untreated specimens[1]

Type drying	Untreated controls	Water-treated controls	Average specific gravity of specimens treated at these retention levels (lb/ft³)[2]			
			0.25	0.6	1.0	2.5
				ACA		
Air dry	0.601 (7.9)	0.596 (7.5)	0.615 (7.7)	0.606 (8.7)	0.613 (6.6)	0.611 (6.4)
Kiln dry		0.599 (7.7)	0.592 (6.7)	0.598 (8.2)	0.607 (7.5)	0.601 (6.0)
				CCA-I		
Air dry			0.595 (7.3)	0.590 (8.8)	0.600 (6.6)	0.599 (6.4)
Kiln dry			0.597 (6.1)	0.581 (8.3)	0.586 (6.3)	0.620 (6.6)
				CCA-II		
Air dry			0.600 (7.9)	0.590 (7.3)	0.599 (8.0)	0.587 (8.2)
Kiln dry			0.588 (7.2)	0.588 (7.2)	0.598 (7.0)	0.599 (7.3)

[1] Values in parentheses are coefficients of variation.

[2] Nominal retention levels; actual retention levels are given in Table A1 of the Appendices.

Average losses for unadjusted MOR values range from none for the airdried 0.25 lb/ft³ treatments with ACA and CCA-II to nearly 20 percent for the air-dried 2.5 lb/ft³ treatment with CCA-I. At the intermediate levels of treatment (0.6 and 1.0 lb/ft³) the loss exceeded 10 percent for kiln-dried CCA-I treatments and was slightly less for CCA-II. Although nearly all treatment cells, including those treated with water only, show some reduction, the DMRT does not indicate significance at the 5 percent level for reductions less than about 10 percent. Five of the 24 treatments caused a statistically significant reduction in MOR. After adjustment for moisture content, none of these five treatments were significant.

For WML, the minimum loss was about 2 percent due to the 0.25 lb/ft³ treatment with CCA-II and ranged to 53 percent for the 2.5 lb/ft³ treatment with CCA-I. The DMRT showed that treatments with both CCA-I and CCA-II caused statistically significant reductions at retention levels of 0.6 lb/ft³ and higher. The air-dry 0.25 lb/ft³ level of treatment with CCA-I also caused a significant reduction. For ACA the 2.5 lb/ft³ level was significant as was the kiln-dry 1.0 lb/ft³ treatment. After adjusting the data to 12 percent MC, a significant reduction was still evident in 14 of 16 cells that initially showed significance.

Table 6.—Levels of significance for main and interaction effects[1]

	Modulus of rupture	Modulus of elasticity	Work to maximum load	Moisture content
Main effects				
Preservative systems	0.0001	0.8739	0.0001	0.0001
Retention levels	.0001	.7055	.0001	.0001
Type drying	.0339	.7290	.0023	.0169
Interactions				
Pres × ret	.1164	.0493	.0001	.0001
Pres × drying	.3325	.7023	.3014	.0103
Ret × drying	.7165	.1750	.4098	.0012
Pres × ret × drying	.4701	.6136	.5921	.0446

[1] Numbers less than 0.05 indicate significance at the 5 percent confidence level.

Table 7.—Levels of significance for main and interaction effects after adjusting modulus of rupture and work to maximum load data to 12 percent moisture content[1]

	Modulus of rupture	Work to maximum load
Main effects		
Preservative systems	0.3954	0.0001
Retention levels	.4313	.0001
Type drying	.0100	.0014
Interactions		
Pres × ret	.1525	.0001
Pres × drying	.1767	.2497
Ret × drying	.8987	.4074
Pres × ret × drying	.4962	.5501

[1] Numbers less than 0.05 indicate significance at the 5 percent confidence level.

Table 8.—Regression equations and 95 percent confidence limits for a new observation at RETL = Z_1, SG = Z_2

The general form of the equation:[1]

$$\text{Strength property} = \hat{\alpha}_0 + \hat{\alpha}_1 Z_1 + \hat{\alpha}_2 Z_2 \pm K \sqrt{\frac{1 + \frac{1}{n} + (S_{22}(Z_1 - \bar{X}_1)^2 - 2S_{12}(Z_1 - \bar{X}_1)(Z_2 - \bar{X}_2) + S_{11}(Z_2 - \bar{X}_2)^2)}{n(S_{11}S_{22} - S_{12}^2)}}$$

Preservative system	Drying condition	$\hat{\alpha}_0$	$\hat{\alpha}_1$	$\hat{\alpha}_2$	K	n	$\bar{X}_1$	$\bar{X}_2$	S_{11}	S_{12}	S_{22}
				WORK TO MAXIMUM LOAD (inch pounds per specimen)							
ACA	Combined	−71	−12	500	89	246	0.888	0.604	0.841	0.0009	0.0019
CCA-I	Combined	−85	−47	530	79	241	.868	.596	.807	.0034	.0019
CCA-II	Kiln	9	−32	370	96	120	.873	.595	.832	.0006	.0018
CCA-II	Air	−52	−18	480	85	123	.885	.594	.857	−.0050	.0021
				MODULUS OF RUPTURE (lb/in.²)							
ACA	Kiln	−11,000	−280	54,000	3,950	123	.877	.600	.831	.0006	.0019
ACA	Air	−7,700	−760	50,000	3,550	123	.899	.608	.858	.0012	.0020
CCA-I	Combined	−9,300	−1,550	53,000	4,050	241	.868	.596	.807	.0034	.0019
CCA-II	Kiln	−6,500	−600	47,000	4,350	120	.873	.595	.832	.0006	.0018
CCA-II	Air	−8,400	−260	51,000	3,500	123	.885	.594	.857	−.0050	.0021

[1] For our purposes the equation strength property = $\hat{\alpha}_0 + \hat{\alpha}_1 Z_1 + \hat{\alpha}_2 A_2 \pm 1.05$ K is a fairly satisfactory simplification.

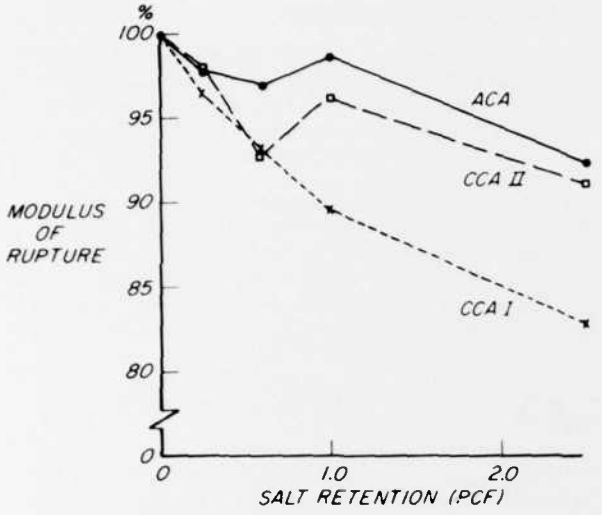

Figure 1.—Effect of salt retention on modulus of rupture for three preservative systems expressed as a percentage of untreated controls (air- and kiln-dried specimens combined and not adjusted for moisture content). (M 151 582)

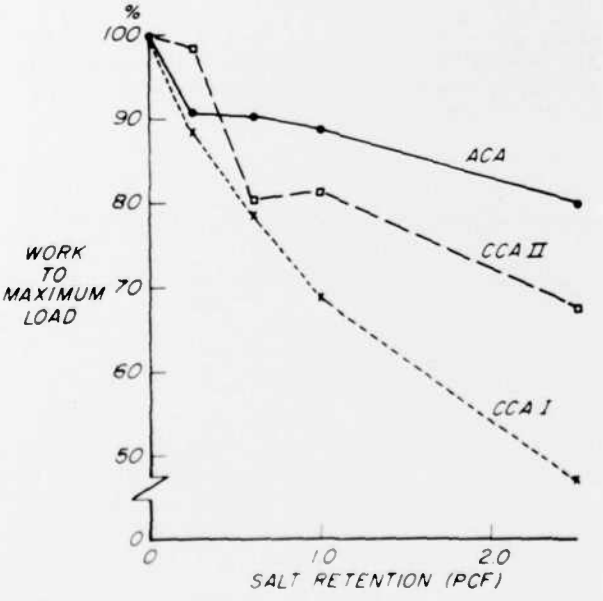

Figure 2.—Effect of salt retention on work to maximum load for three preservative systems expressed as a percentage of untreated controls (air- and kiln-dried specimens combined and not adjusted for moisture content). (M 151 590)

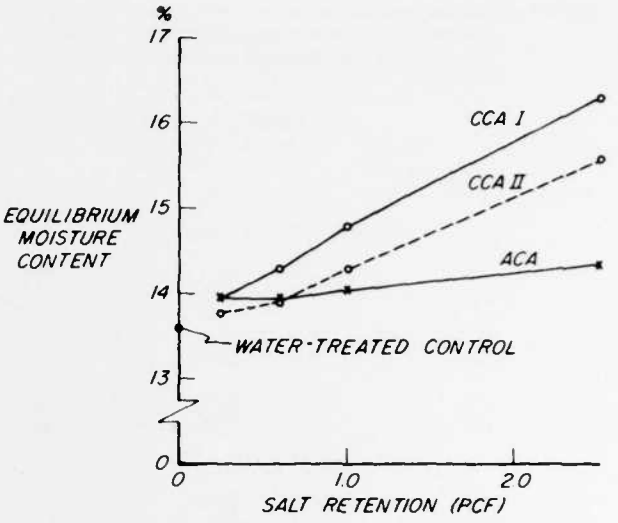

Figure 3.—Effect of preservative systems and retention level on equilibrium moisture content (air-dried and kiln-dried specimens combined). (M 151 583)

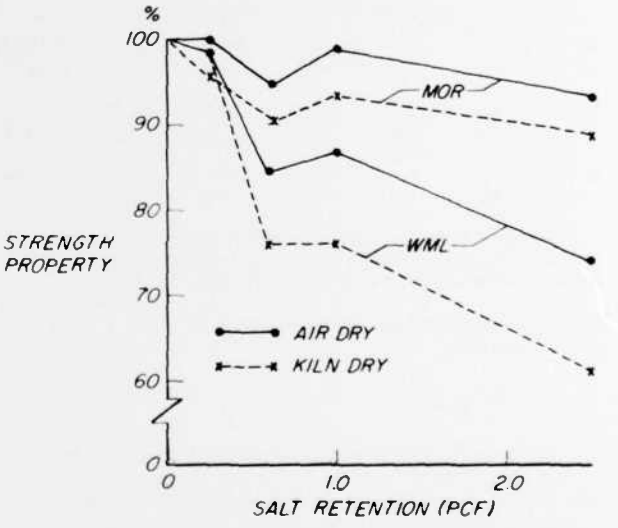

Figure 4.—Effects of air drying versus kiln drying for CCA-II treatments expressed as a percentage of untreated controls (not adjusted for moisture content). WML = work to maximum load. (M 151 585)

Table 9.—Average mechanical properties of treated specimens as a percentage of untreated controls (all percentages are calculated from strength values at test moisture content)[1]

Preservative system	Drying method	Water-treated controls	Mechanical properties of specimens treated at these retention levels (lb/ft³)[2]			
			0.25	0.6	1.0	2.5
			MODULUS OF RUPTURE			
ACA	Air		100.6	96.5	99.7	92.1
	Kiln		94.8	97.6	97.4	92.7
CCA-I	Air	98.5	94.8	96.3	91.1	81.3*
	Kiln	93.9	98.2	89.9*	88.1*	84.2*
CCA-II	Air		100.1	94.8	98.9	93.3
	Kiln		95.7	90.8	93.4	88.9*
			MODULUS OF ELASTICITY			
ACA	Air		102.1	98.0	101.6	95.3
	Kiln		97.3	101.1	102.1	97.9
CCA-I	Air	101.5	96.2	99.6	96.3	101.4
	Kiln	94.6	100.6	97.5	94.7	107.2
CCA-II	Air		99.8	97.9	101.8	96.8
	Kiln		94.8	97.2	98.4	102.0
			WORK TO MAXIMUM LOAD			
ACA	Air		93.1	90.5	92.8	81.4*†
	Kiln		88.4	90.2	84.5*†	78.8*†
CCA-I	Air	93.1	86.8*	83.3*†	70.7*†	47.4*†
	Kiln	89.2	90.3	74.3*†	67.2*†	47.2*†
CCA-II	Air		98.3	84.7*†	86.7*†	74.4*†
	Kiln		98.4	76.0*†	76.2*†	61.2*†

[1] * indicates a significant difference from the untreated controls before adjusting for moisture content; † indicates significant difference after adjusting to 12 percent moisture content.

[2] Nominal retention levels; actual retentions are given in Table A1 of the Appendices.

Kiln drying caused an additional 5 percent reduction in MOR beyond that caused by air drying for all levels of treatment with CCA-II. For WML, kiln drying specimens treated with CCA-II caused additional reductions of about 9 to 13 percent at retentions of 0.6 lb/ft³ and higher. The effects of kiln versus air drying for treatments with ACA and CCA-I were inconsistent across retention levels for all three mechanical properties.

Failure Characteristics

Examination of specimens after testing revealed interesting patterns of failure characteristics among preservative systems, retention levels, and failure types. Normally, brash or brittle failures are associated with wood of low strength, particularly in energy absorption properties. Brashness is common in wood of low density or wood that has been exposed to any agency of deterioration such as decay, heat, or reactant chemicals. Thus it was anticipated that kiln-dried specimens would be more brash than air dried; that high retention specimens would be more brash than low retention; and that specimens treated with preservative systems causing the greatest strength reductions would be most brash. Using complete separation of the specimen at time of failure as our criterion for brashness, we see that the specimens do not adhere to these anticipated patterns (table 10).

For example, in the 2.5 lb/ft³ treatment with ACA, 15 air-dried specimens failed with complete separation while only 8 kiln-dried specimens did. In 7 of 13 cases, the number of air-dried specimens with brash failures exceeded the number of kiln-dried specimens with brash failure (table 10).

In the air-dried CCA-I treatment, 11 specimens treated to 0.25 lb/ft³ failed completely compared to only 1 of those treated to 2.5 lb/ft³. In no case did the numbers of specimens showing brashness increase consistently with increasing retention level.

Based upon strength response, treatment with CCA-I at the 2.5 lb/ft³ level should have caused the most brashy failures. Yet, only one specimen in each of the air-dry and kiln-dry groups with this treatment failed completely.

Table 10.—Numbers of brashy specimens in each treatment cell

Preservative system	Nominal retention	Air dried	Kiln dried
	lb/ft³		
ACA	0.25	6	13
	.6	10	12
	1.0	10	6
	2.5	15	8
CCA-I	.25	11	5
	.6	7	6
	1.0	8	7
	2.5	1	1
CCA-II	.25	7	10
	.6	5	7
	1.0	8	11
	2.5	15	10
Water	0	9	6

Discussion

The Duncan's multiple range test (DMRT) analysis showed that some treatments caused a statistically significant strength response while others did not. The DMRT has shown that the only treatments to cause a statistically significant reduction (5 pct confidence level) are CCA-I at retention levels 0.6 lb/ft³ and higher and CCA-II at 2.5 lb/ft³ when kiln dried. For WML, significant reductions were observed in response to all three preservative systems. The retention level at which significance was observed varied among preservative systems and with type of drying. However, from the general trends evident in table 9 and figure 2, it would seem that all three preservative systems caused reductions in WML at all levels of retentions. Because of high variability the experiment was too insensitive to detect the treatment effects at lower response levels. The same reasoning applies to MOR (fig. 1). Because MOR responded less to treatment than WML, large sample sizes would be required to show significant treatment effects at the low retention levels for MOR.

Similarly, the DMRT only detected statistically significant kiln-drying effects for the CCA-II treatment. Yet, 11 of 16 experimental cells pertaining to MOR and WML for the other 2 preservative systems showed lower results for kiln-dried specimens. Thus experiments with larger sample sizes may also detect significance in the type of drying for the ACA and CCA-I treatments. Furthermore, kiln temperatures were limited to 140°F in this experiment. Higher temperatures would presumably produce more pronounced effects.

From table 8, estimates can be made of the strength reductions due to treatment that can be expected in material treated to conventional salt retention levels.[4] At the 0.25 lb/ft³ treatment level, the reductions in MOR would range from 2 to 5 percent (all calculations assume an SG of 0.6, the average value observed in the experiment; percent reductions will be greater for smaller SG's, less for larger SG's). At the 0.6 and 1.0 lb/ft³ treatment levels, there would be a 2 to 3 percent MOR reduction in the air-dried CCA-II case, a 3 to 4 percent reduction in the air-dried ACA case, and 5 to 7 percent reductions in the other cases. At the 2.5 lb/ft³ level, the MOR reductions would be approximately 4 percent in the air-dried CCA-II case, 17 percent in the CCA-I case, and 8 to 10 percent in the remaining cases.

Reductions in WML at a treatment level of 0.25 lb/ft³ range from 8 to 12 percent. At the 0.6 and 1.0 lb/ft³ levels, WML reductions range from 10 to 14 percent in the ACA and air-dried CCA-II cases, from 16 to 21 percent in the kiln-dried CCA-II case, and from 18 to 26 percent in the CCA-I case. At the 2.5 lb/ft³ level these reductions are approximately 22, 40, and 54 percent.

We observed that when MOR values are adjusted to 12 percent MC, only the drying condition main effect remains statistically significant. Thus the observed decrease in unadjusted MOR as retention level increases is apparently associated with the higher moisture contents in the treated material. On the other hand, correcting work values for MC did not account for the observed reductions in this property. Regardless, moisture adjustments may only be of academic interest. In practice, if treatment causes an increase in the MC of the wood and an associated loss in strength, this must be considered a part of the treatment effect. Effectively, a loss in strength due to increased MC is no different from that due to a chemical degradation of the wood itself.

We noted earlier that we believed that the heavy metal chromium is capable of degrading wood properties. The alignment of the three preservative systems evaluated in terms of the strength reductions observed—CCA-I > CCA-II > ACA—is consistent with this hypothesis. CCA-I has 61 percent chromium (CrO_3), CCA-II has 35.3 percent, and ACA has none.

[4] For example, the control MOR was 22,501. From table 8 we see that in the kiln-dried CCA-II case, the expected MOR value for a retention level equal to 0.25 and a specific gravity equal to 0.6 is = 6,500 − 600(0.25) + 47,000(0.6) = 21,250. Thus the percent reduction would be (22,501 − 21,550)100/22,501 = 4.2.

Conclusions

In small clear specimens, neither ACA- nor CCA-type preservatives adversely affect the MOE of southern pine sapwood either air or kiln dried after treatment to retentions from 0.25 to 2.5 lb/ft³.

ACA has no effect on MOR, but CCA-type preservatives vary in their adverse effects, which may be aggravated by kiln drying.

Work to maximum load is adversely affected by all three preservatives but least by ACA.

Kiln drying at 140°F can adversely affect the mechanical properties of wood treated with certain waterborne preservatives.

Finally, our work clearly indicates that certain preservative systems induce reductions in MOR and WML that far exceed the reductions due solely to processing.

Recommendations

Because of considerable industrial interest in high temperature kiln drying of wood after treatment with these preservatives, additional research is needed to evaluate the effects of the high temperature drying process on treated materials.

Future research should consider species other than southern pine, perhaps Douglas-fir and species in the Hem-Fir group.

Because grade and size factors may interact with treatment effects and because of difficulties with simulating processing effects, the effects of treatments on small clear specimens may not be applicable to full-size structural materials. To adequately account for treatment effects in engineering design, future research must include tests of full-size materials.

Chemical bulking should also be evaluated in full-size material. In bending members, any increase in section modulus due to bulking at least partially offsets reductions in material properties associated with treatments.

The strength reductions caused by the waterborne preservatives evaluated appear to be associated with the amount of chromium in the formulations. The mechanism by which chromium effects wood properties should be studied as a basis for developing alternative formulations.

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Appendix I

Literature

Bending and compression parallel to grain strengths were improved by treatments with 9 kg/m³ (≃0.6 lb/ft³) of chrome-fluoride salts in a study by Burmester *(8)*. He also reported lower impact bending strength which was recoverable if the salt was extracted. Southern pine poles commercially treated with greensalt showed slight increases in bending strength *(12)*, while little or no strength effect was observed in European redwood (Scots pine) treated with about 1 lb/ft³ of acid copper chromate *(18)*.

The influences of 10 types of salt at retention levels ranging from 8 to 24 kg/m³ (≃0.5 to 1.5 lb/ft³) on the mechanical properties of pine, spruce, and beech were investigated by Burmester and Becker *(9)*. Effects on bending strength and on compression parallel and perpendicular to grain strengths varied from slight decreases to slight increases while impact strength decreased significantly. Thompson *(19)* treated rotary cut veneer of four species with Boliden salts, Celcure, Chemonite, and copper chromate. Some species-salt combinations resulted in higher toughness but the toughness of blackgum was reduced from 26 to 52 percent depending upon the chemical.

The mechanical properties of Scots pine treated with 0.25 lb/ft³ of a copper/chrome/arsenate formulation were measured by Hesp *(13)*. The average MOR, impact bending strength, maximum crushing strength, hardness, and shear strength of the treated material were all slightly lower than those of the untreated controls. However, Hesp stated that the means were well within the range of natural variability.

MOR was least affected and the reduction was thought to be of no concern for structural use. In compression parallel to grain and shear tests, the strength reductions in the water-treated controls were as large as those in the salt-treated specimens. Hesp concluded that the reductions observed must be due to pressure treatment with aqueous solutions rather than to any inherent chemical or physical property of the preservative salts.

This is a recurring theme in the literature. Burmester and Becker *(9)* also observed that strength changes are obviously not caused by chemical decomposition of the wood but apparently by the physical treating processes, and that the reductions observed in mechanical properties are of no practical importance. Alexander *(1)* stated, "It is safe to anticipate that round timbers, whether poles or piles, pressure treated to the current specifications of the American Wood-Preservers' Association do not change significantly in bending strength by reason of the preservation treatment."

Both Wangaard *(21)* and Hunt and Garratt *(14)* observed that tests generally show that strength losses are almost entirely due to the temperatures and pressures to which the wood is subjected during the conditioning and impregnation period rather than to a chemical degradation. They indicate that zinc chloride is virtually inactive in the 2 to 5 percent solutions used in commercial practice, although the chemical apparently makes wood somewhat more brittle under impact. However, they add that in high concentrations, particularly in high temperature environments, zinc chloride is capable of degrading wood. These conclusions do not necessarily apply to waterborne salts because of differences in the treating procedures.

Damaging evidence against the waterborne salt treatments is found in the work of Eaton et al. *(11)*. Douglas-fir and southern pine piles were treated with ACA and CCA singly and in dual treatments with creosote. Five piles were tested per treatment group. The average bending strengths of individual treatment groups ranged from about 40 to 80 percent of the untreated controls; MOE from about 55 to 90 percent; and energy required to cause failure from 35 to 65 percent. Generally, the results between species and between salts individually and in dual treatment with creosote were not substantially different. Although large treatment effects are suggested by differences in mean values, many of the differences were not statistically significant because of the small numbers of specimens and the variability in test results. The authors recommend that where mechanical loading is the principle cause of failure, only creosote-treated piles should be considered.[1]

The results of Siemon *(17)* emphasize the inconsistencies in the literature concerning the effects of salt treatments on strength and are in direct conflict with these of Eaton et al. *(11)*. Sixty-four slash pine poles, 14 to 15 inches in diameter at breast height (outside bark), from the three major exotic plantations in southeast Queensland, Australia, were treated to 32 kg/m³ (≃2 lb/ft³) at a depth of 50 mm (2.0 inches). The poles were tested in bending after reaching 30 percent MC at a depth of 50 mm. The average MOR measured was 10,190 pounds per square inch (lb/in.²); MOE was 1,738,000 lb/in.². These values compare favorably with those for untreated small clear specimens of slash pine grown in Australia and tested at 12 percent MC: 10,900 lb/in.² for MOR and 1,370,000 lb/in.² for MOE *(7)*. Although no untreated controls were tested for comparison, it would appear that the reductions, if any, due to treatment with CCA were negligible.

Current engineering design practice does not appear to reflect adequately the potential degradation of mechanical properties by treatment with waterborne salt preservatives. In design with dimension lumber, there is no recognition of treatment effects except in the case of the heavy salt retentions required for marine exposure *(16)*. Even here, normal design stresses apply except that no increase is permitted for impact load duration. In round timber design a 10 percent reduction factor is applied for poles treated by the Boulton process and a 15 percent reduction factor for steam-conditioned southern pine *(2)*. ASTM Committee D07 on wood recently concluded that the reduction for steam conditioning be increased to 25 percent. This change will appear in future editions of the round timber piling standard, but the standard does not recognize the existence of any preservative effect.

[1] Personal correspondence with Oregon State University, where these tests were conducted, revealed that the CCA-creosote-treated Douglas-fir piles failed in shear because of burst checks present before testing. However, this observation does not change the general conclusions of the paper.

Appendix II

Experimental Material

Test material was cut from longleaf pine (*Pinus palustris*) trees 12 inches or more in diameter at breast height from the Harrison Experimental Forest (De Soto National Forest) near Gulfport, Mississippi. Increment cores were used to select trees with potential for providing test material with 6 to 10 rings per inch in the sapwood. Trees having these characteristics were sought to minimize material variability and to assure uniform preservative treatment among specimens.

The first 6-foot bolt above the stump was cut from each of 15 trees. These bolts were end-coated to retard drying and end checking and shipped via motor freight to the Forest Products Laboratory.

Specimen Preparation and Assignment

Each bolt was sawn to maximize the number of 1¼-inch-square sapwood sticks cut parallel to the bark and with the annual rings oriented parallel to one face. Heartwood material was discarded.

Table A1.—Average preservative retentions for treated specimens, ranges, and coefficients of variation (COV)

Preservative type	Type drying	Average retentions of specimens treated at these target levels (lb/ft³)			
		0.25	0.6	1.0	2.5
ACA					
	Air dry:				
	Average	0.243	0.602	1.01	2.59
	Range	0.23-0.26	0.56-0.65	0.97-1.07	2.39-2.81
	COV	(4.4)	(4.3)	(3.7)	(4.5)
	Kiln dry:				
	Average	0.250	0.601	1.01	2.58
	Range	0.23-0.27	0.54-0.64	0.93-1.10	2.41-2.72
	COV	(3.9)	(4.4)	(4.5)	(3.6)
CCA-I					
	Air dry:				
	Average	0.247	0.604	1.00	2.57
	Range	0.23-0.26	0.55-0.67	0.92-1.10	2.33-2.74
	COV	(3.9)	(5.0)	(4.0)	(4.2)
	Kiln dry:				
	Average	0.248	0.601	1.01	2.53
	Range	0.23-0.26	0.57-0.65	0.95-1.09	2.35-2.78
	COV	(3.2)	(3.9)	(3.9)	(4.3)
CCA-II					
	Air dry:				
	Average	0.247	0.605	1.00	2.58
	Range	0.23-0.27	0.56-0.65	0.93-1.08	2.38-2.81
	COV	(4.7)	(4.6)	(4.2)	(4.4)
	Kiln dry:				
	Average	0.250	0.601	1.00	2.55
	Range	0.23-0.27	0.55-0.64	0.91-1.07	2.32-2.72
	COV	(3.8)	(3.7)	(4.1)	(4.6)

The sticks were kiln dried to a target MC of 14 to 16 percent using a maximum dry bulb temperature of 120°F with no wet bulb control, and then brought to equilibrium in a room controlled at 74°F and 65 percent RH (approximately 12 pct EMC).

The sticks were machined to a 1-inch square cross section, the ring orientation trued in the process, and cut into 16-inch lengths, excluding any strength-reducing growth characteristics such as knots and cross grain. From this stock of 1- × 1- × 16-inch specimens the required 680 were selected for uniformity of growth rate and percentage of latewood and for freedom from any small defects that may have been overlooked.

Fifty specimens were randomly assigned to each pair of experimental cells (air vs. kiln drying) that were to receive the same preservative system and level of salt loading (including the water-treated controls), and 30 specimens were assigned to the untreated control group. After treatment, each group of 50 specimens was randomly subdivided for the two levels of drying. (Because of the batch nature of the processing, our "replicates" are not true replicates. However, the carefully controlled nature of the treating and drying processes leads us to believe that between batch variation is of the same order as within batch variation. The analyses of variance support this belief (table A1).)

Treatment

The compositions of the waterborne salt preservative systems were:

	pct
• Ammoniacal copper arsenate	
Copper as CuO	49.8
Arsenic as As_2O_5	50.2
• Chromated copper arsenate, type I	
Chromium as CrO_3	61.0
Copper as CuO	17.0
Arsenic as As_2O_5	22.0
• Chromated copper arsenate, type II	
Chromium as CrO_3	35.3
Copper as CuO	19.6
Arsenic as As_2O_5	45.1

The recommended practice for full-cell treatment was followed *(6)*. An initial vacuum of 27 inches was held for ½ hour, and following solution flow-in at ambient temperatures, a pressure of 150 lb/in.² was applied for 2 hours.

Specimens were weighed and measured before treatment and weighed again after treatment. The concentration of salt solutions required to attain the target loadings was based upon the weight gain of the watertreated controls and specimen dimensions. The 12 separate treatment runs required for the combinations of 3 preservative systems and 4 retention levels were conducted in random order.

Salt loadings were calculated by

$$R = \frac{3.81C\,(W_{TR} - W_U)}{l \times w \times d} \qquad (1)$$

where R = salt loading (lb/ft³)
W_{TR} = weight, treated (grams)
W_U = weight, untreated (grams)
C = solution concentration (weight of salt/weight water plus salt)
l,w,d = length, width, and depth of specimen (inches).

Average salt loadings attained for each experimental cell were very close to target retention levels (table A1). The greatest deviations from target loadings occurred at the 2.5 lb/ft³ treatment where average retention levels ranged from 2.53 to 2.59 lb/ft³ for the six experimental cells treated to that level. Within-cell variation in treatment was also relatively uniform as coefficients of variation were typically 3.5 to 4.5 percent (table A1).

Drying

Air Drying

Specimens designated for air drying were stickered and initially exposed to ambient conditions controlled at 80°F and 90 percent RH for 3 weeks. These specimens were then moved to an environment controlled at 74°F and 65 percent RH and allowed to come to equilibrium.

Kiln Drying

When the study began, industry representatives told us that it was common practice to limit temperatures to 140°F while kiln drying piles treated with waterborne salt preservative. The drying time for piles was said to be about 10 days. Because our specimens were so small and would dry so rapidly, a procedure was needed to retard drying to simulate industrial drying practices.

In the kiln, the specimens were stickered and then wrapped and sealed with polyethelene. The polyethelene was supported so that it did not touch any part of the specimens. Ten extra treated specimens were stickered outside of the polyethelene wrap.

The kiln was then operated continuously at 140°F for 10 days. A 5° wet-bulb depression was maintained to minimize vapor transmission through the polyethelene wrap. By closely monitoring the weights of the specimens outside the wrap, we determined that these specimens dried to about 20 percent MC in 48 hours. Thus, after 8 days the wrap was removed permitting the test specimen to dry within the desired 10-day heating period.

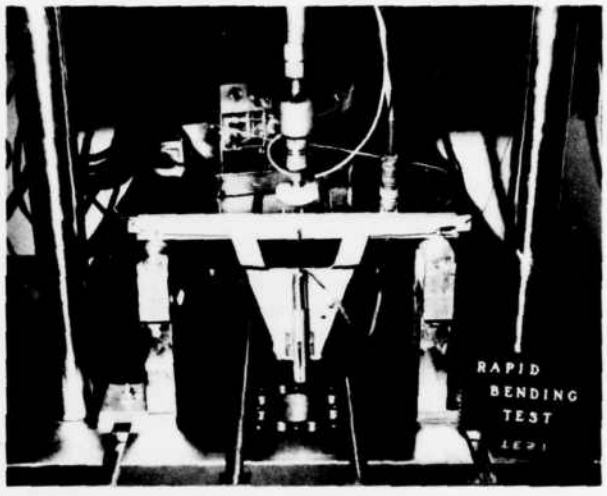

Figure A1.—Closeup of loading apparatus.

We know that this simulated drying technique might increase the chances of seasoning damage. Thermal and chemical degrade in wood is more severe at high moisture levels, and in our simulation the specimens were maintained in a wet state for 8 days. In drying large members, moisture gradients develop which may tend to lower the thermal degrade near the outside. This factor is particularly important in bending members because maximum stresses occur in the outside fibers.

After kiln drying, the specimens were allowed to come to equilibrium along with those that had been air dried in the 74°F 65 percent RH environment.

Testing

The widths and depths of the specimens at mid-length were measured before testing. Immediately after testing, 2-inch-long sections were cut to determine moisture contents and specific gravities. A correction for the weight of salt in the specimens was made in determining MC and SG.

Specimens were tested in bending by applying a concentrated load at the center of a 14-inch span. A linear voltage differential transformer (LVDT) for measuring deformation was supported by a yoke suspended from pins driven into the specimens at the neutral axis over the supports. A pin was also driven into the neutral axis at the center of the span to provide a connection for the LVDT (fig. A1).

The load was applied by an MTS structural test system at a constant rate of 46 inches per second, the maximum capacity of the actuator available. Because of the rapidity of the test (approximately 1/50-second duration), a digital oscilloscope (memory capacity of 4,096 data words) was used to temporarily record the data. This permitted 2,048 paired observations of load and deformation with an elapsed time of 20 microseconds between data points.

High speed photography was used to study the test in progress to assure that the deformation data was accurate. We learned in trial runs that excessive noise in the load-deformation trace was caused by vibration of the pin connecting the LVDT to the specimen. Increasingly larger diameter pins were tried until no further vibration of the pin could be detected by photography. Photography also showed that minimizing the tolerance between the pin diameter and the hole diameter in the stem of the LVDT reduced the extraneous noise in the load-deformation trace. Further, a slight preload greatly reduced the shock and subsequent vibration in the specimen and equipment that was apparent when no preload was applied. A typical load-deformation data trace is shown in figure A2.

The overall test setup including the MTS loading system, the digital oscilloscope, electronic interface equipment for controlling data flow to and from the oscilloscope, and a teletype terminal is shown in figure A3. About 2½ years elapsed between kiln drying the specimens and testing them because of delays in equipment procurement and equipment malfunction during the shake down period. We do not believe that this delay affected the results because the salts are inert in wood at low moisture levels. An additional 3½ months were required to complete the testing. The 680 specimens were tested in random order to eliminate possible time bias during the test period.

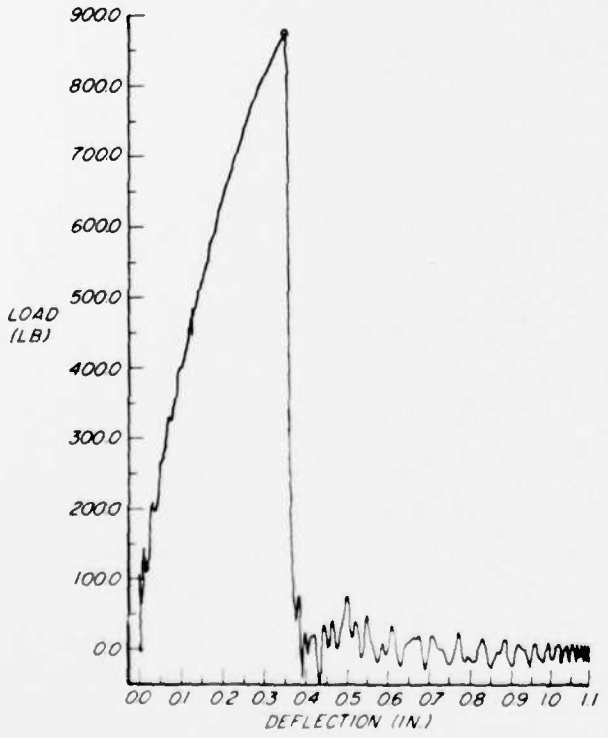

Figure A2.—Typical load-deformation diagram. (M151584)

Property Calculation

Moisture Content and Specific Gravity

MC was calculated as

$$MC = \frac{W_T - W_{OD}}{W_{OD} - W_S} \times 100 \qquad (2)$$

where MC = moisture content (pct)
W_T = weight of moisture specimen at time of test
W_{OD} = weight of moisture specimen ovendry
W_S = weight of anhydrous salt in moisture specimen;

and specific gravity as

$$SG = \frac{W_{OD} - W_S}{16.38(l \times w \times d)} \qquad (3)$$

where SG = specific gravity
l = length of moisture specimen
w,d = cross sectional dimensions of bending specimen as defined earlier.

In determining W_S we assumed that the salt was distributed uniformly along the 16-inch strength specimen. Thus, W_S was determined by applying the ratio of specimen lengths (moisture/strength) to the salt retention calculated by equation (1).

Moduli of Rupture and Elasticity

MOR was computed by the common flexure equation for a beam loaded with a concentrated load at the center. MOE, also calculated by the common flexure equation, is a secant modulus. A secant modulus is the slope of a secant connecting the origin and any *specified point* on the stress-strain curve.

A secant, tangent, or chord modulus is frequently taken to be the MOE for materials that do not conform to Hooke's law *(2)*. Under slowly applied loads, wood normally approximates Hookian behavior and the MOE is usually determined as the ratio of stress to strain below the proportional limit. Under the rapid loading employed in this study, the specimens did not behave linearly and it was necessary to use one of the alternative procedures.

To determine a secant modulus, a cubic spline function was fit to the data between the origin and the maximum load. The modulus is the slope of the secant connecting the origin and the intersection point of the cubic spline function with a vertical line through the 0.125-inch deformation (fig. A2). That level of deformation was chosen to assure that the intersection point for all specimens occurred earlier on the curve than the maximum load.

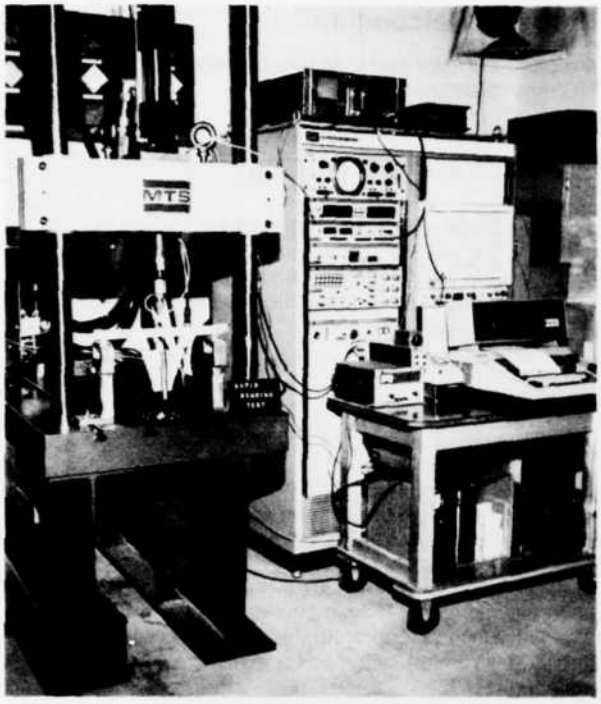

Figure A3.—Overall view of test equipment. (M144969-6)

The secant modulus may not necessarily measure precisely the same material characteristic as the MOE determined by the standard test *(4,5)*. However, the two properties probably respond similarly to treatment. Thus, the secant modulus can be used as an index of the effects that the various treatments used in this study have on the "standard" MOE.

Work to Maximum Load

The energy absorbed by the specimen as it was loaded to failure (work to maximum load) was determined by numerical integration of the area under the stress-strain curve to maximum load *(9)* (fig. A2). For nine specimens, the areas were also measured with a planimeter which assure that the numerical integration could be used without introducing bias in the results.

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Mechanical Properties of longleaf pine treated with waterborne salt preservatives

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In small clear specimens of longleaf pine sapwood, neither ammonium chromated arsenate (ACA) nor chromated copper arsenate (CCA) preservatives adversely affect the modulus of elasticity of wood either air or kiln dried after treatment to retentions from 0.25 to 2.5 lb/ft^3. ACA has no effect on MOR, but CCA-type preservatives vary in their adverse effects which may be aggravated by kiln drying. Work to maximum load is adversely affected by all preservatives tested but least by ACA. The study showed that kiln drying at 140°F can adversely affect the mechanical properties of wood treated with certain waterborne preservatives.

Keywords: Preservatives, CCA treatment, ACA treatment, southern pine, mechanical properties, strength properties


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